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REVIEW

Sense (and) the city: From Internet of Things sensors and open data platforms to urban observatories

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Abstract

Digitalisation and the Internet of Things (IoT) help city councils improve services, increase productivity and reduce costs. City-scale monitoring of traffic and pollution enables the development of insights into low-air quality areas and the introduction of improvements. IoT provides a platform for the intelligent interconnection of everyday objects and has become an integral part of a citizen's life. Anyone can monitor from their fitness to the air quality of their immediate environment using everyday technologies. With caveats around privacy and accuracy, such data could even complement those collected by authorities at city-scale, for validating or improving policies. The authors explore the hierarchies of urban sensing from citizen-to city-scale, how sensing at different levels may be interlinked, and the challenges of managing the urban IoT. The authors provide examples from the UK, map the data generation processes across levels of urban hierarchies and discuss the role of emerging sociotechnical urban sensing infrastructures, that is, independent, open, and transparent capabilities that facilitate stakeholder engagement and collection and curation of grassroots data. The authors discuss how such capabilities can become a conduit for the alignment of community- and city-level action via an example of tracking the use of shared electric bicycles in Bristol, UK.

KEYWORDS

IoT and mobile communications, smart cities applications

1 | INTRODUCTION

Urbanisation is one of the four demographic megatrends that reshape the human community along with population growth, ageing, and migration. As cities grow, the logistics required to ensure their essential services become more challenging for city councils. These challenges include increased demand for resources such as water and energy, pollution and environmental impacts, persistent inequality, ageing infrastructure etc. [1]. Many of these challenges are tracked and detailed in relevant reports relating to sustainable development goals (e.g. [2]). In confronting urban challenges, cities embrace technology to expand their services and enable citizens to share the benefits. In this context, cities experiment with emerging technologies such as the Internet of Things (IoT) that provides the ability to understand the physical environment through the collection and analysis of granular data, allowing better decisions to be made. The IoT has already been helping lighten human workload by enabling automation and increasing efficiency [3], as well as improving Quality of Life (QoL) [4]. As a growing platform of billions of devices connected to the Internet and each other mostly through wireless networks, IoT can be essential to solving social and governance challenges, such as air pollution and increased traffic. The reach of IoT is not only limited to the city government to enhance and optimise cities as a whole but can ‘flow down’ to devices that urban dwellers can use to improve their personal daily lives, to experience a higher QoL. Similarly, digitalisation takes advantage of digital technologies to change business processes and workflows to improve business models and allow digital transformation. Data generated by IoT devices provide information about the city's progress in terms of Key Performance Indicators, defined by authorities to measure multiple areas. City authorities may track a city's progress against KPIs, measuring IoT recorded parameters such as air quality, the percentage of household waste that is reused, recycled, or composted, and the proportion of energy-efficient homes. For example, Belfast city council and Bristol City Council (BCC) have released their 'One City Belfast' agenda [5] and the One City Plan [6], respectively, where they have identified indicators that measure city progress.

City authorities have been actively collecting and making such city-related information available for some time. For example, the City of Chicago was one of the pioneers of opening up urban datasets for public use through its online data portal[1] and embraced urban sensing through collaborations with researchers and innovators on projects such as Array of Things [7]. Other initiatives in cities are driven by non-government stakeholders, such as the University of Michigan's Urban Collaboratory[2] which provides an opportunity for interdisciplinary faculty and students to work with city stakeholders.

The opportunities offered through IoT implementation and digitalisation are wide, but there are many challenges associated with the complexity of managing both the generated data and the devices. Understanding citizen concerns and addressing these is also critical. In this paper, we explore and categorise data generated at different levels of urban organisation, from the individual to their immediate built environment, to their surrounding community and eventually at city-scale. We map the processes of such data generation across levels and discuss the value proposition that insights based on the analysis of this data can have.

We then briefly explore the challenges faced in urban data collection (§ 3.2) and consider the different city- and national-level responses to urban data management challenges (§ 3.1). We explore how the Urban Observatory (UO, § 3.1) concept addresses these challenges by facilitating the collection, storage, and analysis of city data, while also serving as a platform to garner support and collaboration from city stakeholders and researchers united in tackling urban issues. We discuss how one such entity, the Bristol Infrastructure Collaboratory (BIC), brings together city stakeholders and researchers to undertake interventions in urban spaces including the monitoring of infrastructure assets [8], the interaction between complex transport infrastructures and people in 'shared spaces' [9], managing residential energy assets [10], the monitoring of water quality [11], citizen-driven air quality sensing [12] etc. We discuss in detail an e-bike use case study (§ 3.3) to demonstrate how an entity such as the Collaboratory can support mobility interventions in the city.

The paper is structured as follows: Section 2 discusses IoT's capability for data collection at personal, built environment, district, and urban levels. Section 3 introduces urban data challenges and how UO and the BIC in particular approach these challenges, exploring the different areas highlighted earlier with a detailed case study about a mobility intervention in the city. Section 4 concludes the paper with our final thoughts.

[1] https://data.cityofchicago.org/
[2] https://www.urbanlab.umich.edu/

2 | BACKGROUND: MAPPING SENSORS, THE IoT AND BIG DATA IN URBAN SPACES

Based on the location of its generation, its use and how data collectors and users change, IoT-generated data can be viewed as falling within four logical layers: personal, built environment, district and urban. In this context, IoT describes the emerging technological capability of interconnecting inanimate objects (such as sensors, controllers, TV sets, wearable devices, thermostats, lamps, etc.) with one another and accessing data related to their status, typically over the Internet. Data generated at different levels is intrinsically linked (§ 3.3), and data generated at one level can be aggregated and used at a different level.

Such data can be generated from a multitude of activities. It can come from well-established applications that people have used for years, or proof-of-concept projects, piloted on a small scale or proposed only in a laboratory environment. Understanding and differentiating between different levels of data generation (and essential parameters such as granularity and frequency) facilitates data curation. Such descriptions can improve citizens' and city officials' understanding of what data is collected and stored and increase transparency and trust in data collection schemes. It can also simplify data reuse by application developers, as sensor data feed creators are expected to describe the produced data harmoniously.

2.1 | Personal IoT data collection level

Table 1 and Figure 1 summarise the use of IoT on a personal level. Wearable devices with sensors, such as activity trackers, measure different physical activities such as step counts, calories burnt, sleep tracking, and floors climbed, which help keep track of an individual's health. Wearable sensors may also help identify signs of critical health incidents such as stroke traumatic brain injury [13] in patients. They have also been extensively used for the recognition of activities of daily living [14]. For people who may not prefer wearable devices, or are unable to use them, there are even everyday objects instrumented with sensors. Sleeping beds have been fitted with sensors to monitor heart rate, respiratory signal, movement activity of sleep posture, and sleep quality, providing sleep analysis and detection of sleep-related problems [15]. Pressure or force sensors can be integrated into sofas or chairs to detect and avoid poor body postures that harm health and cause pain and other complications [16]. The flow of hot and cold water can be measured in bathrooms or kitchens to monitor water used during a bath and usage of drinking water [17], which could help monitor health indicators.

TABLE 1 Internet of things usage at the personal level.

Activity	Source	Items measured	Analytics value proposition
Exercises/ sleeping	Smart watch/fitness tracker	Heart rate, calories burnt, steps taken, floor climbed	Identify sharp activities for stroke and traumatic brain injury (TBI). Self-monitoring of health
Activities in bathroom	Electrocardiogram, photoplethysmogram, ballistocardiogram	Heart rate, blood pressure	Health and well-being of an individual
Sleeping	Pressure sensors in or under the bed/body-worn altimeter/tilt sensor	Heart rate, respiratory signal, sleep posture, movement activity and quality of sleep	To improve sleep analysis and detection of sleep problems; detects and alerts when a person leaves the bed
Sitting	Pressure or force sensors	Body posture while sitting on the chair or sofa	To avoid the adverse effect of poor sitting behaviour and posture which can link to pain and other complications
Water intake	Water flow sensors	Hot and cold water usage	Monitoring water usage in kitchen/ bathroom to determine if elderly people are drinking water at regular intervals
Mental well-being/ social interaction/ self-journal	Mobile application	Occasions where people showed gratitude; social application (Facebook/ WhatsApp) usage	Monitor mental and emotional well-being for vulnerable people. Depending on multiple parameters and worrying situation, carers can be informed

Personal health applications provide individuals with information on their health and fitness and allow them to set and follow personal health goals and care from their medical providers. Individuals can use personal health applications to exercise regularly, improve cardio fitness, move throughout the day, reach sleep goals, track their menstrual cycle, or practise mindfulness with breathing exercises to stay relaxed and focused. Health applications help users understand their health and well-being. The health insights can motivate the citizen

FIGURE 1 Internet of things use at the personal level.

leading to a change in behaviours. In addition to walking, citizens also cycle or use e-bikes to travel and may want to know their cycling statistics.

In addition to 'physical health measures', 'mental well-being measures' are metrics for assessing well-being. Such applications provide regular meditation routines, deep breathing exercises assisted by visuals and haptic feedback, and request a moment to pause and reflect on a thought or an action. Users can use applications to remind them to breathe or reflect throughout the day. Other applications enable users to feel grateful or thanked and help feeling good and stimulate positive feelings about life. Mobile applications promoting gratitude [18] have been created to foster gratitude and assess social connectedness.

2.2 | IoT data generated at built environment level

People spend approximately 15.7 h per day [19] at home and the rest at work or outside. It is also estimated that we spend around 80% of our time within the built environment that surrounds ours. The number of hours at home increased further during the pandemic (2020/21) when people went outside only for essential services. Data can be collected by the occupant or the entity maintaining a house/office. Table 2 and Figure 2 summarise the usage of IoT at the built environment. The use of IoT at this level can contribute to efficiency, security, environmental protection, and usability/accessibility.

2.2.1 | Energy efficiency and utilities management

From an efficiency perspective, occupants can optimise lighting and heating of homes/offices. An individual can use a motion sensor to turn on and off lights based on the presence of humans, saving energy and reducing operational costs [20].

TABLE 2 Internet of things usage at a building level—house/office.

Entity	Activity	Sources	Items measured	Analytics value proposition
Room (living/dining/bedroom); office space	Lighting	Motion sensors	Human presence	To switch lights on and off to save energy costs
	Heating	Motion sensors	Human presence	To set the heating based on the presence of people and direct the heat to people rather than heating the entire room
	Safety check	Door and window sensors	Doors/windows (open/closed status)	To ensure doors/windows are closed for safety and heating/cooling efficiency
	Movement monitoring	Video-based system/depth-based cameras	Human functional movements	To detect dangerous events such as a person falling or abnormal gait patterns
	Indoor air quality (IAQ) monitoring	Air pollution sensors	Air pollutants such as asbestos, biological pollutants, CO, CO2, sulphur oxides, volatile organic compounds (VOCS)	To understand causality and reduce irritation of the eyes, nose and throat, headaches, dizziness and fatigue or respiratory diseases, heart disease and cancer
	Energy monitoring	Smart plugs/Energy monitors	Energy usage	To determine energy usage by different appliances and co-relate based on the occupancy of the building space and determine the efficiency of the building materials
Kitchen	Grocery list	Bar code scanner	Smart bins scan items bar code	To automatically create a grocery list, sync it to the phone application and order automatically
	Recycling	Bar code scanner	Smart bins scan items bar code	To inform the user whether the product could be recycled or not and how it can be recycled
	Product expiry date	Bar code scanner	Date of manufacture, best use before and expiry date	To track expiry date, optimise usage of ingredients and help reduce food waste
	Gas/smoke monitors	Natural gas and CO monitor	Levels of natural gas and CO in the air	To detect gas buildup from a leaky or forgotten stove and avoid accidents.
Other-area (garden/parking/utility)	Solar power generation	Solar panels/smart flower panels	Energy generated, useable and extra energy	Scheduling charging of EV, washing machines or dryers to utilise renewable energy and send the extra energy generated back to the electric grid
	Plant moisture sensing	Moisture sensors	Moisture level	Identify when the plant needs watering, based on the moisture levels, the gardens and plants can be watered automatically using stored rain-water
	Parking information	Parking sensors	Proper or improper car parking	Identify whether the car has been parked correctly. It can also help in detecting theft (modern key-relay attacks)
	Water flows	Temperature/volumetric sensors	Temperature and usage of water	Optimise hot/cold water usage and reduce water wastage
	Rainwater harvesting	Rain sensor (pluviometer)	Amount of rain	To harvest rainwater for toilet flushing, clothes washing, garden watering; also reduce the probability of urban flooding by managing storm-water discharge during heavy rainfall

They can use thermostats to automatically set room temperature based on room occupancy to save energy. For example, MIT's Senseable Team created a system, 'Local Warming' [21] that directs the heat to where the people are present rather than heating the whole room, resulting in energy savings. Humidity sensors in bathrooms can automatically turn on an exhaust fan.

Citizens can monitor the energy usage of their house/office space with smart plugs (connected to household appliances such as kettles or televisions), or electricity metres attached to

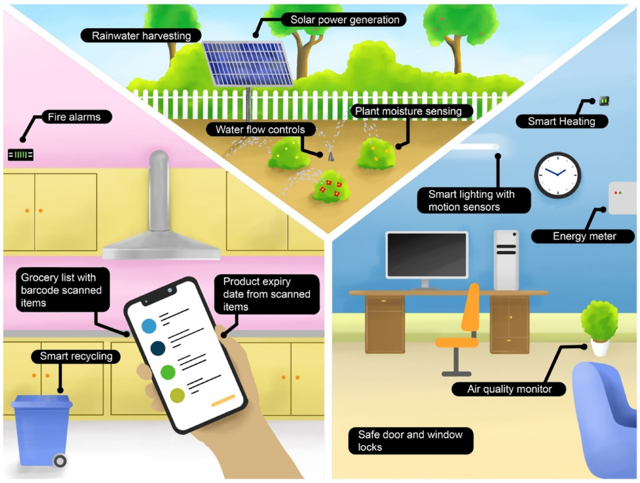

FIGURE 2 Uses of Internet of things at the built environmental level.

the main inlet for electricity. Electricity companies have begun to instal smart metres that allow citizens to monitor their energy consumption half-hourly, daily, monthly and yearly. The electricity usage data helps to understand and break down the electricity charges for the user, understand what appliances use most of the energy, and how to reduce consumption and related charges. 3e-HOUSES[3] and TwinERGY[4] implemented IoT technologies in social housing and provided an innovative set of services for energy efficiency. Such projects incorporate digital intelligence to allow citizens to actively adapt their consumption to market fluctuations with the help of data and automation. IoT technologies provide real-time monitoring and management of energy consumption, integrate renewable energy, and create resources to reduce energy consumption. Such projects and IoT technologies enable citizens to change their consumption behaviour, reduce costs, and improve QoL. Citizens also increasingly use electrified means of mobility (from cars to bicycles) to travel and need to charge them regularly; it is essential for energy companies to understand user requirements for charging depending on a vehicle type.

IoT-enabled devices can facilitate solar power generation, moisture detection, parking sensors and rainwater harvesting. Citizens can generate renewable energy using solar panels [22] to reduce dependency on brown energy [23]. They can schedule the use of washing machines and dryers or the charging of Electric Vehicle (EV) during the day when solar energy is generated [24] or at night when electricity tariffs may be cheaper. Furthermore, citizens can sell surplus electricity generated back to the electric grid using feed-in tariffs [25].

Water supply interruptions cause significant problems for customers [26]. IoT technologies can help the practice of rainwater harvesting [27] to use for flushing toilets, washing clothes, and watering gardens by storing rainwater in underground tanks. The practice of saving rainwater improves resilience in two ways: firstly, it helps reduce the amount of mains water required; secondly, it can be used when the regular water supply is interrupted [28]. It also helps to reduce stormwater discharge from heavy rainfall, reducing the probability of urban flooding and pollution [29]. IoT can also play an essential role in maintaining gardens by sensing the moisture in plants/gardens to determine when plants need water and can be automatically watered using stored rainwater.

2.2.2 | Security and safety

Citizens can monitor doors and windows (open or closed) using IoT sensors, helping regulate temperature. The number of occupants in the buildings can be determined using mobile phones and Wi-Fi signals [30]. Depending on the occupant, the room door can be opened or closed. This helps during guest visits, for example, opening the door remotely to a plumber who visits to fix a pipe. IoT devices can monitor babies or the elderly. Video-based systems (depth-based cameras) are used to analyse functional movements of a child or a patient [31], alert systems to detect dangerous events (e.g. a person about to fall [32]) walking movements, and identify specific types of dementia [33]. Parking sensors are installed at home to determine whether the car has been parked correctly. Additionally, it helps detect the vehicle (e.g. the car moved from its position during an odd hour). It also helps to detect recent key-relay attacks [34] on vehicles such as Tesla. Innovative home products such as Amazon Alexa and Google Home provide multiple functions to protect the home using indoor and outdoor cameras, smart doors, and efficient heating and lighting using motion sensors and learning user preferences.

IoT devices are also handy for detecting smoke and where gas/smoke detectors are a legal requirement such as in the UK; they could become an integral part of a home that can detect smoke, Carbon Monoxide (CO) or natural gas leaks. Instrumented bins can monitor waste types and quantities and even inform their user of the recyclability of a product [35] for proper disposal.

2.2.3 | Indoor environment

From an environmental perspective, there are a number of urban challenges that digital innovation can help with. For example, bad IAQ irritates the eyes, nose and throat, causes headaches, dizziness, and fatigue (immediate short-term effects) or respiratory diseases, heart diseases, and cancer (long-term effects) [36]. There are multiple indoor air pollutants such as asbestos, biological contaminants, CO, formaldehyde/pressed wood products, lead, nitrogen dioxide, pesticides, radon, indoor particulate matter, second-hand smoke/environmental tobacco smoke, stoves, heaters, fireplaces and chimneys, and volatile organic compounds. Citizens can use IoT devices (such as Smart Citizen Kit [SCK] [37], Luftdaten [38], Atmotube [39]) to measure environmental parameters of (IAQ) around their house and install air filters to purify the air.

[3] https://kwmc.org.uk/projects/3ehouses/
[4] https://www.twinergy.eu/

Bespoke environmental sensors developed by research projects such as SPHERE[5] or TwinAIR[6] are also used to monitor IAQ. Measuring IAQ over time helps to collect data and answer questions such as the effect of burning candles or cooking on IAQ and opening windows/doors for cross ventilation to improve IAQ. With growing awareness of air pollution worldwide, air filters and better indoor quality are a top priority for most urban cities.

In addition to IAQ, citizens can measure indoor environmental conditions such as temperature, humidity, barometric pressure, and luminosity. The data help answer questions on the effect of indoor environmental conditions on the room occupants' health and the impact of humidity causing the room's walls' dampness in the house. SPHERE [40] developed home sensors to diagnose and help manage health and well-being conditions, allowing early diagnosis, lifestyle change, and the ability of patients to live at home.

2.3 | IoT data gathering at district level

So far, we have discussed data collection at a personal level and from within our immediate built environment, referring to examples of relevant innovation. The district level we identify here relates to neighbourhood-scale monitoring and the surrounding area where a citizen resides. We specifically look at the use of IoT/digitalisation in mobility, liveability, and community building, as they relate to this context. Usually, most district-level parameters, from footfall to local school performance, are of interest to authorities and may become available to citizens for use. Table 3 and Figure 3 summarise the usage of IoT at the district level.

2.3.1 | Mobility

Mobility and accessibility are significant issues in urban life. Mobility refers to the physical movement measured by trips, distance, and travel time. In contrast, accessibility refers to the ability to reach desired goods, services, activities, and destinations [41]. In addition to distance and travel directions, availability of data around the environment (air quality/temperature, wind speed/direction, traffic delays), location of EV charging points, car parking spots and availability would be beneficial from a traveller's perspective. For cyclists, information such as cycling routes, cycle repair shops, and public bike pumps can help navigate the city using bicycles. From an accessibility perspective, knowing the options available for disabled parking and disabled access to the building and stores is also beneficial. Cycle routes used by the citizens can help transport planners plan cycle routes and help health officials understand the long-term impacts of cycling on citizens.

[5] https://www.bristol.ac.uk/engineering/research/digital-health/research/sphere/
[6] https://twinair-project.eu/

2.3.2 | Liveability

Perceived safety and opportunities for leisure and accessibility of essential services are crucial for all citizens. In this sense, historical and real-time air quality data and surface levels and water quality help citizens understand the liveability of a neighbourhood. Information regarding schools, such as the number of students attending classes and school performance, can help parents choose a suitable school for their children. Crime maps could provide detailed information on the rates of various types of crime. Knowing the location of parks and green spaces is essential for relaxation purposes. Trees Near You[7] provides information about different species of trees and their environmental benefits and allows citizens to connect with nature. Information such as recycling bank locations and the type of waste recycled is useful. In addition, comprehensive information on QoL may explain factors related to the levels of happiness of citizens. It is measured by multiple indicators, such as inequality in health, lifestyle, community, local services, and public perceptions of living. Traditionally, QoL indicators are obtained from annual surveys of neighbourhoods. Data of this nature is commonly made available by local authorities via open data platforms (e.g. in the UK, Open Data Bristol[8] or London Data Store[9]).

2.3.3 | Community building

Sharing resources becomes essential when the focus moves from a single individual to the community. People can share vehicles and ride with strangers by carpooling, borrowing a power tool, and more, all with the click of a button. An example of sharing resources is Peerby,[10] sharing food is Shareyourmeal[11] and Olio.[12] Helpfulpeeps[13] is a social marketplace for local help and allows people to ask for help and offer help.

Restaurant owners can use mobile applications to promote local food within the community containing descriptions and addresses of local food outlets with discounts for locals followed by a local food fair. Customers can be credited with a stamp (food outlet logo) to promote the relationship and the goodwill factor (e.g. Milton Keynes organised the MK Food Revolution [42] to promote local food.). To reduce household plastic waste, shops can allow residents to buy dry bulk goods such as pasta, rice, flour, and beans in reusable containers, thereby reducing non-recyclable packaging waste. Communities also organise neighbourhood competitions to organise events or healthy competitions (such as singing and running). HoodChampions[14]

[7] https://tree-map.nycgovparks.org/tree-map/learn/about
[8] https://opendata.bristol.gov.uk/
[9] https://data.london.gov.uk/dataset
[10] https://www.peerby.com/en-nl
[11] https://sharethemeal.org/
[12] https://olioex.com/about/
[13] https://www.seedrs.com/helpfulpeeps
[14] https://www.hoodchampions.sg/

TABLE 3 Internet of things usage at a district level—useful information for citizen in neighbourhood and surrounding areas.

Entity	Source	Items measured	Analytics value proposition
Mobility information	Google maps/ Bristol open data	Air quality, temperature, wind speed/direction, traffic delays	To plan the journey and reroute traffic to manage pollution
		Empty parking and charging points	Real-time availability of a parking spot near the citizen and EV charging points
		Cycling route, public bike pumps, cycle shops and repairs	Help citizens explore the city by using bicycles
Neighbourhood information via open data	Bristol open data/ city council website	1. Trees/parks and green spaces 2. Air and surface water quality 3. Recycling banks 4. QoL such as to measure of inequality in health, lifestyles, community, local services and public perception of living in the city. 5. Crime map 6. Children school-specific data	1. To create awareness about the environmental and monetary benefits of trees and also make available information about the different parks and green spaces available. 2. To determine the livability of the neighbourhood. 3. To provide information about recycling points in the city and what kind of waste is recycled. 4. To access and improve the QoL for the citizens. 5. To provide details about the different types of crimes happening in the neighbourhood and what actions are taken by the authorities including progress in different cases. 6. To access the quality of education in the schools and improve it.
Community efforts via social networking websites	Mobile applications	1. Descriptions and addresses of local food outlets with discounts for local people 2. Items purchased, usage and wastage 3. Renting resources shared between residents 4. Neighbourhood competitions 5. Skill set of the local population 6. People willing to share food to those in need of it. 7. Mental and physical health of residents 8. Lactating moms and breastfeeding hubs	1. To promote local food, reduce food wastage and promote relationships and goodwill factor. 2. To reduce waste from households, provide reusable containers to reduce non-recyclable packaging waste. 3. To enable people in the neighbourhood to request and share items to facilitate an efficient use of resources. 4. To organise events such as singing, running to create more gracious and happening hoods. 5. If someone needs to learn a new skill, they can find someone in the neighbourhood who can teach that skill set. 6. To match older people in need of food with those who want to share their meals or share excess food voluntarily. 7. To reduce the feeling of loneliness by organising social meet-ups for those who can be benefited from it. 8. To promote breastfeeding within the neighbourhood with a map detailing the best locations and also provide information about why you should breastfeed, how to breastfeed and finding help in the local area.

promotes citizens to contribute to their neighbourhood, help each other, and create more welcoming and happening neighbourhoods in Singapore. Strava [43] tracks human exercise, mainly cycling and running, using global positioning system (GPS) data and incorporating features of social networks.

Wellness promotions can be organised regularly to improve citizens' mental and physical health. Such initiatives help reduce the feeling of loneliness among people through social gatherings and challenges. Walkers Group Santander developed a mobile application for citizens to organise social walking events [44], and Walk in the city (another app) challenged seniors through the use of gamification [45].

2.4 | Urban scale IoT uses

National governments and city councils strive to ensure that cities are liveable and to demonstrate their policies by providing details about the steps they take to create a better life for citizens. The aspects discussed in this section are of interest to policy officers for decision-making, or used for urban planning and to meet specific regulatory standards, and are often provided to the citizens through open data platforms. For this, city councils monitor multiple parameters such as environmental, localised information, transport/mobility, and crowd-sourced data. Figure 4 summarises the use of IoT technologies on an urban level. Tables 4 and 5 summarise the

FIGURE 3 Internet of things use at the district level.

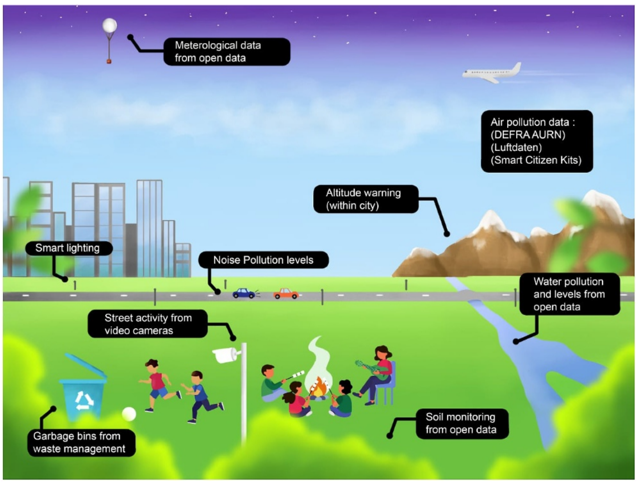

FIGURE 4 Internet of things at an urban scale.

environmental factors governments may monitor and the citizen services they could provide to citizens, respectively.

2.4.1 | Environmental factors

Authorities may collect information on air quality, temperature, humidity, and barometric pressure of a city and surrounding areas by installing high-quality high-precision sensors. For example, Automatic Urban and Rural Network is the UK's largest automatic monitoring network that reports compliance with ambient air quality directives. City councils often measure air quality using sample diffusion tubes placed at monitoring locations and collected over a few months making limited observation points for effective policy-making around pollution risk mitigation. To circumvent that, IoT technologies with environmental sensors can transmit the readings periodically, reducing cost and increasing productivity for city councils. Project UMBRELLA[15] has deployed more than 200 nodes spread throughout the South Gloucestershire region and a few nodes at Cardiff University [46] that contain air quality sensors. Similarly, Project Eclipse installed 115 low-cost solar-powered urban environmental sensors connected using a cellular network in Chicago to monitor pollution at fine spatial and temporal resolutions [47]. Furthermore, the government encourages citizens to install low-cost sensors (such as SCK or Luftdaten) and make the data open or available to the city council. Air quality data sensors installed in public buses or bin lorries are a low-cost solution to collect data about the whole city regularly [48]. City councils can monitor sources of air pollution such as power plants, road transport, household heating, agriculture, and industrial processes. Air pollution data helps understand its source (construction/wood burning/traffic conditions/fireworks on Diwali and New Year nights). Combining air pollution with meteorological data allows air quality predictions to be made, to understand how it is affected by different seasons (e.g. in winter, people might burn more wood to keep rooms warm; rain reduces air pollution) and to inform policy on what measures can be taken to reduce its impact. Measures such as encouraging parents to opt for more sustainable transportation by providing information on the Air Quality Index around schools during drop-off and pick-up times; diverting traffic temporarily [49] can improve air quality. The knowledge gained can provide inferences from the above data that can help predict air quality in the region and take action accordingly.

City councils also measure quantitative (i.e. volume) and categorised data (i.e. the type of noise such as traffic, construction noise, and bird sounds) in the city. A noise map can serve as one of the QoL indicators and can influence citizens' well-being, which is also helpful to citizens when planning to move to a new location to identify an area with less noise pollution [50]. In addition, noise maps help construction companies fine-grain and optimise the materials they use to reduce noise pollution. Sensitive microphone devices capture short clips of real-time ultrasonic and audible noise from bats, birds and other wildlife, traffic, and human activity. Data is used to analyse the effect of noise and pollution on animal behaviour, determine the activities of the bat population around the meadows, the pattern of human activity during different seasons of the year, and source of the noise generated (e.g. cars, trucks, people). Sound sensors are attached to smart street lamps in public spaces to detect specific sounds such as gunshots, car alarms, screams, fighting, and sound levels in bars and cafes. Such systems may help law enforcement authorities detect and prevent incidents.

Apart from air and noise pollution, a city council can measure water quality data (e.g. pH, ammonia) and water flows in surface water bodies (e.g. water depth, speed). Water quality is essential in water treatment plants (provided to city homes for drinking) and water bodies for water sports. Monitoring and managing water levels in ports/water bodies can save energy (pumping water to maintain water levels) or avoid flooding. Sensors are used to monitor soil moisture and vibrations to detect a dangerous pattern of land conditions to warn about the risk of floods, landslides, and other natural hazards. City councils also record meteorological data, such as

[15] https://www.umbrellaiot.com/

TABLE 4 Internet of things usage at the urban level—environmental parameters collected by the government and analytics obtained.

Entity	Source	Items measured	Analytics value proposition
Air pollution	DEFRA AURN/ Luftdaten/SCK	Air temperature (°C) Relative humidity (%rh) Ambient light (lux) Barometric pressure (kPa) Particulate matter (PM1/2.5/10) (ug/m3) Equivalent carbon dioxide (ppm) VOCS (ppb) Ozone (ppm) Nitrogen dioxide (ppm)	To understand 1. The impact transport mode selection has on air quality, with specific attention given to the areas around schools. 2. What are the peaks of air pollution at schools/train stations/coach stations/airports at the time of arrival and departure of students/trains/coaches/aeroplanes, respectively? 3. The impact of weather (e.g. rain) and different seasons on air pollution. 4. Whether the air pollution can be reduced by temporarily diverting the traffic around the area of concern. 5. Combine with wind velocity data to identify the impact of specific pollution sources. 6. Allows comparison between the pollution contributions of 'stop/start' and 'steady flow' traffic. 7. Which days/weeks are good and worst for air pollution? 8. Predict air quality in the region based on the above parameters.
Water pollution/ levels	Bristol open data	pH, dissolved oxygen, temperature, turbidity, electrical conductivity, chlorophyll, nitrate, ammonia, chloride, rhodamine, hydrocarbons and water levels, water speed in surface water bodies	1. To determine water quality and find ways to contain or improve the current situation. 2. To monitor and reduce flooding.
Soil monitoring	Cosmic-ray soil moisture monitoring network	Soil moisture, vibrations	To detect dangerous patterns in land conditions and warn about floods, landslides and avalanches
Meteorological data	Bristol open data, WunderGround, met-office	Solar energy, rainfall, wind speed/direction	To predict rainfall, hurricanes and solar energy generation capacity
Altitudes (within the city)	Ordnance survey, Google maps	The elevation of different roads in the town	1. To help pedestrians, cyclists, motorists and disabled people to plan trips accordingly. 2. Useful for predicting surface water flooding.
Noise pollution	SCK	Noise volume (dB) and type of noise	1. To utilise the noise map in determining life quality and its effect on citizens health. 2. To help construction companies fine grain and optimise the building materials to reduce noise more effectively. 3. To capture ultrasonic and audible sounds of bats and birds and other wildlife, traffic, human activity in real-time to determine: a. How active is the bat population in the area? b. Does traffic noise change animal behaviour over a day? c. What is the pattern of human activity during different seasons of the year? d. What are the sources of the noise generated?
Sound patterns	Noise sensors	Specific sounds such as gunshots, car alarms, screams, fighting and sound levels in bars and cafes	To help law enforcement authorities in detecting and preventing incidents
Street activity	Video cameras	Number of people crossing an intersection, or utilising a park	1. To provide insights to city authorities on improving services or take appropriate actions to manage crowds. 2. CCTV is also used for law enforcement and traffic management.
Smart lighting	Street lighting organisations	Approaching or going pedestrian or traffic	To save energy by dimming lights when no one is around and brighten it when people/traffic is approaching it
Rubbish bins	Waste management—City council	When the garbage bins are full and need to be replaced	To optimise the collection of garbage and provide city authorities in utilising the staff more efficiently

TABLE 5 Internet of things usage at an urban level—parameters measured by the government to improve citizen services.

Entity	Source	Items measured	Analytics value proposition
Citizen statistics	Bristol open data	Monitoring localised information Statistics about population growth, crime, marital status, religion and employment Monitoring parking spaces	To: 1. Provide conversational interfaces in order to make urban data more accessible and engaging to citizens. 2. Provide the real-time location of public vehicles such as emergency vehicles (police, ambulances, fire), buses, public taxis, trains, waste bin trucks etc., to address critical situations in the shortest time. 3. To help locate the nearest parking space and pay online, reducing time in finding a parking spot, and CO emissions, less congestion.
Citizen mobility	Travel services operator	Monitoring vehicles mobility	To deduce the people travelling patterns via trains, bus, boats and taxi's to figure out most crowded stations/routes and how to improve services for people, for example, support the faster movement or add more trains/buses To help in predicting the impact on stations (if any planned/unplanned work comes up) for which customer communications and operational plans need to be implemented
		People travelling patterns	To understand: 1. Which route or platforms do people use? 2. Do they take the first train or wait for a less crowded one? 3. Do people choose the fastest route or the most comfortable? 4. How do customers move around sophisticated stations? 5. To track from which and what regions vehicles are entering and exiting to and from the city?
Citizen mobility	Open data	(Anonymous) real-time mobile locations of the citizens	To understand: 1. How neighbourhoods are used in a day? 2. How the distribution of buses and taxis correlates with densities of people? 3. How goods and services are distributed in the city? 4. How different social groups, such as tourists and residents, inhabit the city?
Feedback data	Crowd-sourcing platforms	Crowd-sourcing data—Citizen feedback	To allow citizens to provide information about the city and help the government provide better services The citizens can: 1. Install sensing kits to measure air pollution, humidity, and temperature; locate and report potholes and upload the data to crowd-sourced maps. 2. Report flooding/broken streetlights/potholes to the crowd-sourced maps. 3. Use the website to propose, debate and vote on ideas for improving the city.

the amount of rainfall and solar energy, to estimate the energy demand of households [51].

Other information, such as wind speed and direction, is measured in different parts of the city. Cyclists can use this information to alter their route and avoid severely windy roads, or bridge owners can preventively close bridges. It helps to plan where to place domestic wind turbines and predict the amount of energy generated. Wind speed and direction combined with the altitude of different city roads help pedestrians, cyclists, motorists, and disabled people better plan their trips.

City councils use sensors to determine street activities, such as the number of people (pedestrians/cyclists) crossing an intersection or using a park with cameras, a microphone, and edge computing [7]. The data provide insights to city authorities for improving citizens' services or taking appropriate action to manage crowds in the city centre (e.g. informing law enforcement if necessary). Thermal cameras can also be installed near harbours and water bodies to detect people who may fall into the water.

A city council provides street lighting to promote urban security and make roads and pathways safer. The city council must resolve street lighting problems as soon as possible to avoid a potential accident. Streetlight teams run periodic manual checks by driving along stretches of road to check if street lights are showing normal behaviour, turning off and on when they are supposed to, which is costly and requires traffic disruption. UMBRELLA monitors street lights using a camera and a machine learning model, allowing the streetlight team to remotely monitor the street lights.

As councils upgrade their lighting infrastructures by moving towards Light Emitting Diode lighting, they can also further improve the savings by combining lighting with sensors to detect movement [52], so the lights may be dimmed when no one is in its vicinity. Finally, a city council can use smart bins [53], which can compress garbage and inform authorities when they are full. This system provides authorities with information to send their staff out for collection only when required.

2.4.2 | Localised information

A country is usually divided into counties, and a county is divided into wards. City councils keep information on population growth, crime, marital status, religion, and employment. Eventually, they can provide an interactive platform for citizens that provide conversational interfaces (powered by chatbots), making urban/city data more accessible and engaging to citizens, replacing current visual-based interfaces [54]. The real-time location of public vehicles such as emergency vehicles (police, ambulances, fire), buses, public taxis, trains, and waste trucks is also recorded and provided to address any critical situation in the shortest time possible. Cities with city operations centres can coordinate emergency city services such as hospitals (ambulance), fire, police, transport providers (bus, rail, airport), and mental health services in the community. They also monitor different CCTV cameras and traffic junctions in the city. Having a coordinated response between various agencies, they would respond quickly and prevent emergencies [55].

2.4.3 | Transport—Mobility

City councils and governments can collect data on the purchase of cars, trains, buses and tickets to determine the mobility patterns of citizens/vehicles. Transport authorities can deduce people's travelling patterns from taxis, busses, trains and boat ticketing to figure out the most crowded stations and how to improve services for people (e.g. adding more trains based on the number of people using the service). The insight also helps predict the impact on stations (if any planned/unplanned work comes up) for which customer communications and operational plans need to be implemented. Transport for London (TfL) uses their knowledge [56] about commuter routes to understand the choices made by commuters, such as the routes/platforms used, the trains they prefer (congested train/earliest train/fastest route/most comfortable), and their movement around complex stations. Additionally, TfL encourages people to avoid busy stations by making travel cheaper outside the city rather than through the middle. Working with mobile phone company authorities can also create real-time visualisations using mobile phone signal data to reveal the dynamics of the city, that is, anonymous movement patterns of people and transportation systems to determine the common usage of streets and neighbourhoods [57]. By anonymously combining the mobile location of citizens with the movement of public transit, pedestrians, and vehicular traffic and overlaying the data on the city map, governments can generate real-time maps that help us understand the use of neighbourhoods during the day. Data help to understand the correlation between the distribution of buses and taxis with the densities of people, the distribution pattern of goods and services in the city, and the travel patterns of different social groups, such as tourists and residents. The knowledge gained helps local transport authorities optimise transport services.

With the help of Automatic Plate Number Recognition, the city can analyse vehicle movements across its border and the number of vehicles with petrol, diesel, hybrid and electric vehicles. The authorities can compare the number of vehicle types over time to understand how air pollution depends on the kind of vehicles and the acceptance of electric cars by the citizens. City authorities can also combine vehicle mobility data with asphalt-embedded parking space sensors, allowing the system to direct drivers to the nearest available parking space. For example, Barcelona implemented a parking application, 'ApparkB', to locate the closest parking space and pay online [58]. The benefits are faster parking, fewer CO emissions, and happier and healthier citizens. The city council is also responsible for road infrastructure, road markings, and road signs to guide drivers. However, faded lane markings and graffiti street signs make it difficult for drivers to follow the road signs and potentially endanger themselves or others. BigClout project [59] used edge machine learning to implement a road damage detection application to monitor the transport infrastructure, resulting in increased productivity and reduced costs for the council.

2.4.4 | Crowd-sourcing data

Citizens have been working with governments to provide feedback and suggestions to improve the working of city council and government in a variety of ways. Digitalisation has improved these processes and improved accessibility, ease, and resolutions. Improved systems use open data platforms (e.g., on a map) where citizens can use low-cost environmental sensing kits to measure air pollution, humidity, temperature, bump sensors (on bicycles) [60] to measure bumpiness on the road and upload data to crowd-sourced maps. They can also report flooding/broken streetlights/potholes to crowd-sourced maps and open up decision-making via proper channels such as the website. Each month, the city council can select the most popular ideas from the website and implement financially viable projects proposed by citizens. For example, initiatives such as Paris' Madame Mayor, I have an idea' [61], Iceland's 'Better Reykjavik website' [62] and French platform Carticipe [63] allow citizens to propose improvements in the city on a map, debate issues, and vote for their favourite ideas. Platforms such as Ushahidi [64], OpenStreetMap [65] and Shareabouts [66] are mapping applications for crowd-sourced information gathering which can be used. CycleStreets [67] is a crowd-sourced cycling-specific travel planner. Of course, such approaches presume citizen engagement, potentially relevant skills development and access to supporting infrastructure, which for a variety of reasons is not always in place. Many scholars have raised concerns about the potential for increasing inequality instead (e.g., [68] among others).

3 | INNOVATING WITH URBAN DATA AND ITS CHALLENGES

In Section 2, we explored the many ways in which digitalisation and the IoT can inform and support decision-making at each of the different levels we focused on. We also discussed the potential value proposition of analysis of the collected data and summarised these in the tables above. However, data analysis is only possible when the data is collected and made available to be processed and analysed safely and securely. As discussed, there are many challenges involved with data collection and processing, such as privacy, complexity, cost, citizen engagement etc. (Section 3.2).

As a way of illustration, citizens using electric bicycles might find useful a number of metrics and statistics at a personal level; parameters such as mileage, journey times, and speed can be useful both in real time (when cycling) and for later reflection (e.g. in understanding potential health benefits). At the same time, at the built environment level, energy suppliers might benefit from knowing the demand for charging the batteries of electric bicycles. If there was to be a serious uptake of this mobility modality, they could plan their supply to match the patterns of mobility and the associated energy requirements, ensuring that facilities that may need it (e.g. university campuses, transport hubs, households in targeted neighbourhoods) are timely serviced. Therefore, information about battery use, status and charging could be shared, transcending personal data collection and integrating with the planning of supply at the subsequent level. Similarly, at the district/urban level, health officials might benefit from cycling data to understand the long-term impacts of cycling, and transport agencies might benefit from understanding the uptake of cycling routes. In this case, collecting data from bike use and distributing it via appropriate forms at all levels is complex and potentially requires custom-designed hardware and effort in the integration of collected data in some meaningful way and even some standardisation, where any benefits of replication and scaling become apparent and desired elsewhere. However, if a citizen purchases an electric bike today, they may have access to such data individually, and it is still difficult for other stakeholders (energy suppliers, planning and health officials, transport agencies, etc.) to have access to appropriate forms of such data (sanitised/aggregated/anonymised, etc.).

We discuss in further detail the many challenges faced across this value chain (i.e. the interrelated processes that create this value) in the following paragraphs, starting from policies and platforms aimed at supporting innovation all the way to the deployment of relevant testbeds.

3.1 | Responding to urban challenges by enabling digital innovation

Local authorities have launched several initiatives to improve their cities in terms of fairness, health, sustainability, resilience, equality, diversity, environment, aspiration, and success for everyone, based on IoT deployments and quality data to tackle the challenges caused by urbanisation. At the same time faced with the realities of urban data management as discussed earlier, they have developed initiatives to enable leveraging on the data whilst mitigating risks from unintended consequences. In Bristol, UK, for example, the local city council (BCC) has launched a climate emergency plan [69] and committed to being carbon neutral and climate resilient by 2030. They have identified 10 key areas: transport, buildings, heat decarbonisation, electricity, consumption and waste, business and the economy, and others. BCC has launched their One City Plan [6], which sets an ambitious vision for the future of Bristol until 2050. The plan is built on six themes: connectivity, health and well-being, homes and communities, economy, environment, learning and skills, supported by key enablers such as culture and technology. Connectivity and technology are explicitly recognised enablers and the Council built upon its experience of working city stakeholders (universities, civic organisations, etc.) to deliver smart city research and interventions, including developing its city-operating centre [55] and providing citizen-centred solutions. Technology plays a key part in the development of solid evidence based on urban data that measure the city's progress and support the success of the One City Plan and climate emergency plan. For Bristol, in particular, long-hailed for its digitalisation agenda and ranking highly in smart cities surveys (e.g. topping the UK's Huawei Smart Cities Index for 2017), an ambitious programme of work has been set [70].

There are other initiatives in the UK aimed at facilitating innovation based on harnessing the value of data generated as we discuss here. For example, the Connected Places Catapult[16] is a UK-based technology and innovation centre that aims to help cities, businesses, and governments create connected places for people to live, work, and travel. It was created by the UK government's innovation agency, Innovate UK, and focuses on bringing together technology companies, academics, and public sector organisations to address challenges in areas such as mobility, transport, and the built environment. The Catapult works with a wide range of partners to help accelerate the development and commercialisation of new technologies and services, providing access to funding, expertise, and facilities. This includes providing support for startups and small and medium-sized enterprises, facilitating collaboration between companies and academic institutions, and working with local and national governments to develop policy and regulatory frameworks. In addition to its support for innovation, the Connected Places Catapult also plays a key role in driving economic growth and job creation, helping to build the UK's

[16] https://cp.catapult.org.uk/

reputation as a world leader in urban innovation and technology. Through its work, the Catapult aims to create sustainable, connected places that are better for people, the environment, and the economy.

At the UK national level, the Department for Digital, Culture, Media, and Sport initiated the Secure Connected Places programme[17] that aims to support the development and deployment of secure and resilient connected places technologies in the UK. SCP focuses on creating secure and trusted environments where new technologies can be developed and tested. This includes technologies such as smart transport systems, autonomous vehicles, and IoT devices. The programme aims to identify and address the security challenges associated with these technologies, including cyber threats and privacy concerns, to ensure that they are deployed safely and effectively, as stated in a recent survey of connected places in the UK [71]. SCP brings together industry, academia, and government to collaborate on research, innovation, and the development of new standards and best practices. The programme also supports the testing and demonstration of new technologies in real-world environments, including the creation of a network of testbeds and trials across the UK. Overall, it is focused on creating secure and connected places that support economic growth, enhance public safety, and improve QoL for people in the UK.

Other Government investment emphasised the importance of R&D in the areas of infrastructure and cities and the development of integrated testbeds. For example, the UK Collaboratorium for Research on Infrastructure and Cities (UKCRIC) consortium was funded to provide a network of facilities and methodologies (including dedicated spaces, testbeds, methods and tools) for research, innovation, pedagogy, and collaboration. UKCRIC was established as a distributed research capability in response to the perceived need for the investment and regeneration of UK infrastructure [72]. It attempts to focus on problem-specific challenges, such as climate change, that cannot be solved by one organisation [73].

In addition to large-scale laboratory facilities designed to meet the challenges related to physical infrastructure, a network of collaborating 'Urban Observatories' hosted by different universities was developed to increase the understanding of how cities function and to support decision-makers in managing the city infrastructure through the use of IoT and adoption of digital technologies, a process also referred to as digitalisation. Urban observatories have been developed as model entities by UN-Habitat [74]. Their original model was devised to help find creative solutions for urban data collection and analysis in partnership with cities around the world. Urban observatories are well-positioned to address the frequently expressed need for reliable, high-resolution urban datasets, specific to the cities and immediate city-regions in which they operate. They assist in strengthening data capacities at national, sub-national, and local levels, providing platforms to facilitate effective knowledge exchange and promote evidence-based governance built on a shared knowledge base. UKCRIC's vision describes the function of its observatories as entities that generate evidence concerning infrastructure development, as seen in Figure 5.

Urban Observatories consist of five major components: a stakeholder network that helps operationalise it, data, a data dissemination platform, an observatory support system and a decision support interface [74]. Thus, a UO provides a platform for collecting, modelling and analysing data, with the aim of informing decision-making on a local, city, regional and national scale. UOs help stakeholders understand challenges and perform evidence-based interventions. UOs promote platforms as accelerators of change and innovation to support decision-making and develop infrastructure delivery and operational insights. They provide go-to places to help other cities establish observatories by sharing learning and best practices.

Currently, six observatories have been set up in Newcastle, Bristol, Sheffield, Manchester, Birmingham, and Cranfield. The different UOs have different focuses based on the expertise of the host university. However, they are aligned in fulfilling technical aspects, such as designing and deploying urban sensing networks, data curation, and providing analytics to turn data into information. The focus is on creating a co-learning and co-production environment that stimulates and supports full participation. This accelerates smart city planning and long-term, evidence-driven strategic and operational deployment (innovation and change).

UOs also foster collaboration between people and organisations interested in infrastructure. UKCRIC UOs will continue to address urban challenges, drawing on practical experience from the network to enable the next generation of infrastructure innovation. Resources and data are shared and available for download, allowing researchers to access data from other cities. It also helps researchers work on problems requiring multi-city data access for insight development.

To date, much of the output of UO has been the development of methodologies for the deployment of low-cost sensor networks and the analysis of data from these networks [8]; however, more work is required to understand how

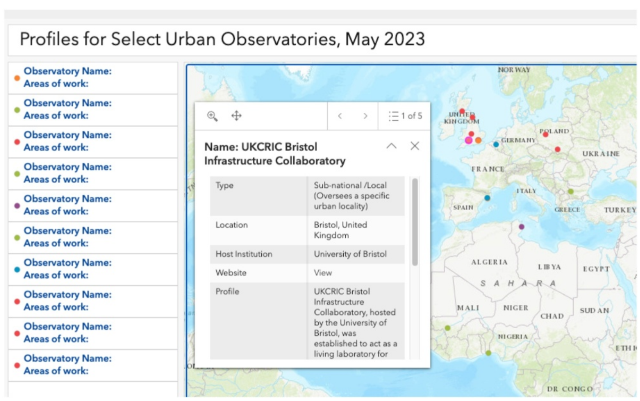

FIGURE 5 Bristol Infrastructure Collaboratory entry at the UN-Habitat website.

[17] https://www.gov.uk/guidance/secure-connected-places

this data and analysis can be used to support decision-makers in implementing meaningful change [75, 76].

3.1.1 | The Bristol Infrastructure Collaboratory

The BIC (or simply 'Collaboratory') was formed under the principles of UKCRIC UOs to support researchers/organisations in the city by collecting urban data that can be used for analysis and collaboration. It also embodied the core principle of seeking alignment of the notions of the living lab, innovation districts and information marketplaces, as its researchers have identified this as a building block of smart cities [77]. Living Labs are open innovation ecosystems in real-life environments using iterative feedback processes to create a sustainable impact throughout a lifecycle approach [78]. Innovation districts are geographic areas where leading-edge research institutions and companies cluster and connect with start-ups, business incubators and accelerators [79]. Information marketplaces are created where the creation and exchange of values are facilitated by data, such as personalised transport planning based on real-time traffic information [77].

The Collaboratory was viewed from early on as a process for delivering 'soft infrastructure', that is, the people, networks, relationships, and processes to enable the technology to work. That soft infrastructure is a conduit for brokering meaningful collaboration between local/international stakeholders aimed at urban innovation to deliver next-generation infrastructure systems.

Over the years of its existence, it supported a collection of cross-domain activities and projects, ranging from people-space interaction to asset monitoring and energy systems, including, for example,

- Development of living lab capabilities in micro-generation, transactive energy and performance monitoring by installing several smart energy systems, including photovoltaic and local storage systems, in single- and shared-owner homes. Data is currently being collected to understand the impact of these systems and how energy savings brokerage can be implemented (e.g. TwinERGY project [10]).
- Supporting "Urban Vision" [80] that aimed to understand the impact of different visual patterns in an environment on health and well-being. The Collaboratory facilitated the set up a travelling exhibition [81] consisting of a walkable corridor installation. Researchers monitored participant's movements, visual cognitive processing load, reaction times, and gait kinematics using retro-reflective markers attached to different body parts, detected by a motion capture system and additional cameras.
- Contributing to the structural health monitoring of the Clifton Suspension Bridge in collaboration with its managing Trust [82] by collecting vibration and displacement data from the bridge and developing new methods to characterise pedestrian and vehicle traffic [8] to improve bridge safety and optimise maintenance.
- Deployment of low-cost water quality sensors measuring pH, dissolved oxygen, temperature, turbidity, electrical conductivity etc. to understand the built environment's impact on water condition and quality and provides an early warning for floods. A multi-parameter water quality monitoring system [11] has been deployed in Bristol's floating harbour demonstrating the feasibility of collecting and presenting high-frequency real-time water quality data.

This is a small sample of relevant activities and project support, with a more detailed case to be presented later as an opportunity for reflection on how such capability can help mitigate the challenges discussed.

3.2 | Urban data collection challenges

Despite a host of innovation support mechanisms and policies that may be in place, smart city initiatives often fail to leverage the anticipated value from urban data [83], or to scale up or replicate [84] across geographies. A number of challenges and barriers exist, from the deployment of equipment in the real world to the perceptions of citizens about new technologies installed in their neighbourhoods. In the following paragraphs, we will explore some of these.

3.2.1 | IoT infrastructure

Deployment Smart city R&D projects often deploy IoT infrastructure, including cloud, edge and endpoint devices, to collect, analyse and visualise data. There are multiple challenges faced by such deployments ranging from understanding project requirements and designing to specification to setting up the infrastructure to ensure that different components work together in the real world as tested in the lab.

Requirements analysis and deployment challenges are project-dependent and depend primarily on citizen preferences, communication between stakeholders, and expectations of different collaborators/partners. Designing the IoT infrastructure involves challenges in ensuring the platform's end-to-end security and having a resilient infrastructure in terms of network bandwidth, device interconnection, thermal efficiency and power supply. It also includes data-related challenges such as storage space, volume reduction, management of access, integration, harmonisation, curation, availability, and even monetisation and liability.

It is also essential to understand how various users/devices/applications are authenticated and authorised, including how the relevant credentials such as passwords or encryption keys are stored securely. Implementing IoT infrastructure presents challenges regarding provisioning devices and ensuring their network connectivity is reliable and secure. Challenges include understanding how the applications will be deployed on the IoT devices and ensuring compatibility between different hardware architectures. With the increased number of hardware devices and software installed, it is essential to perform accounting and monitoring functions platform-wide.

Furthermore, there are challenges around the scalability, modularity, extensibility, adaptability, and reproducibility of IoT infrastructure. IoT deployments often rely on severely constrained (in terms of processing, storage, and networking capabilities) battery-powered wireless embedded devices. Such devices are generally difficult to manage and often suffer from multiple security vulnerabilities [85].

3.2.2 | Privacy

With the ever-increasing number of IoT devices, that capture many physical parameters, citizens' privacy is potentially at risk. Multiple physical parameters can be combined to understand an individual's habits, their presence, or even their activities at home [86]. For example, it is possible to track an individual's movements inside their house [87], correlate them with metadata gathered by a Wi-Fi router, and draw a timeline of the activities of a person. In terms of government services, law enforcement agencies have piloted facial recognition cameras in public places [88] to detect people with a criminal record. China's government has developed a social credit system [89] to rate citizen trustworthiness by calculating their credit score based on financial activities, including shopping habits, traffic tickets, taxes payments and leisure activities [90]. Challenges in relation to the collection of personal information are about users' privacy and how the information is used by third parties such as, for example, a tracking kit provider. Exposure of such data to anyone other than the specific person is problematic by definition as it contains Personally Identifiable Information, unless shared explicitly by the owner or in a form that protects anonymity (e.g. aggregated data).

Built environment-level challenges are related to user privacy, security and identification of activities. For example, data on lighting, heating, IAQ, and energy monitoring can inform on house occupancy and identify activities such as cooking, bathing and watching television; information about recycling and shopping lists can be used to identify a homeowner's eating habits. Additionally, using IoT solutions at home could become a security risk. For example, web-enabled CCTV cameras being hacked, digital door locks malfunctioning or being remotely broken into, leaving the occupants outside their houses. Consumers have seen a flood of IoT products aimed at domestic use (smart plugs, washing machines, ovens, lighting, and baby monitors). Many appliances can now be purchased with IoT-enabled features. They improve QoL by allowing easier access and management, reducing costs and increasing productivity [91, 92]. But on the other hand, it can make a home more vulnerable to cybersecurity breaches (as seen recently when baby monitors were hacked) [93].

At the district level, datasets relating to area services or local features may inadvertently contain data about individual citizens (e.g. from applications that allow sharing of goods and services). Privacy implications of many of these depend on the application privacy agreements and policies and how well they comply with the regulatory environment they operate in.

Urban scale data provides information on city life and is generally anonymised, as it does not relate to any specific individual [94]. Using such data that may originate from mobile phone operators or application providers can lead to skewed analysis if users turn off tracking/Bluetooth or have enabled privacy-preserving options. It is also important to note that data access can also create more inequality; since more QoL parameters about neighbourhoods are known, wealthier people may tend to relocate more than citizens who do not have such awareness. [95].

3.2.3 | Infrastructure costs and value for money

There are significant capital and operational costs associated with the IoT infrastructure [96], and city councils must understand the benefits and return of investment in sensor installation and maintenance. Costs include the requirement for regular upgrades and replacements of sensors, potentially due to natural hardware failure or vandalism. Another maintenance cost comes from the effects of normal or extreme weather events that damage the IoT infrastructure.

Data accuracy depends on sensor quality (low-cost vs. high-cost) and location (near vs. far). City authorities can improve the accuracy of the data by installing more sensors, thus increasing the granularity of the data. However, it also increases installation costs and presents challenges to data scalability. This may also raise a question whether the energy cost of running billions of IoT devices outweighs its benefits [97].

Another bottleneck for Smart City projects is achieving financial sustainability [98]. Initial funding often comes from government, but this rarely covers long-term operational costs, and an ideology of open data leaves few avenues for revenue generation. It has been suggested [98] that, often, innovative city projects focus on deploying the technology rather than the application and outcome, making the transition to financial sustainability difficult.

3.3 | An urban intervention case study: Supporting a mobility intervention in the city of bristol

As part of the city's Horizon2020 Lighthouse Project REPLICATE (Renaissance of Places with Innovative Citizenship and Technology) Collaboratory, researchers equipped 12 electric bicycles (e-bikes) with usage monitoring devices over 2 years to support a mobility intervention. This intervention was originally intended to support observations about multimodal electric mobility for the combined use of EVs with e-bikes. However, due to the impact of COVID-19, it was repurposed to support the sustainable mobility of care workers in the city and to understand the aspects of the transition to more sustainable transport, in the form of shared electric bike schemes. These were deemed a potential future transport option due to Bristol's hilly topography.

3.3.1 | Requirement analysis and system design

Albeit commercial bicycle tracking devices exist in the market, a monitoring device had to be created from scratch that was capable of harvesting energy internally from the e-bike battery. Creating a custom device was required as existing bicycle monitoring devices required periodic charging by the user, leading to a significant sample bias. The direct connection to the electrical system on the e-bike also presented an opportunity for improved monitoring. E-bike electrical systems have multiple components (primarily the battery, drive, and user interface). These communicate via the Controller Area Network (CAN) bus to enable the operation of the e-bike. Analysing CAN bus messages provides insights into electrical drive output, pedal torque, battery status, and much more.

Figure 6 provides a system diagram for the e-bike mobility monitoring system.

① A single-board computer (SBC) (Raspberry Pi Zero W) was used, but with several enhancements to enable its operation as a mobility monitoring device. A GPS was integrated, communicating via Universal Asynchronous Receiver/Transmitter with the SBC. This provided location information and a real-time clock. A CAN bus interface was implemented, allowing SBC to monitor the internal communications of the e-bike. A power manager was developed that allowed the SBC to harness power from the host e-bike, and an internal battery was fitted, which meant the device could run diagnostics and upload data even after the e-bike was switched off.

Several communication technologies were implemented in the tracker. Wi-Fi was used for bulk data upload at the end of journeys by logging into an access point, if one was available. ② and ③ LoRaWAN was also implemented and used to transmit periodic updates while mid journey, including the location and battery status of the e-bike.

④ When connected to Wi-Fi, the monitoring device securely uploads records (via an ssh tunnel) to an e-bike monitoring server set up to receive, process and visualise the harvested data.

⑤ Uploaded log files were batch-processed, and each measurement was passed through the Kafka message broker into a time-series database (InfluxDB), all running on the same machine. Other services and processing scripts subscribed to this Kafka broker stream and performed any processing necessary to interpret the data, such as decoding raw CAN messages. Processed outputs were published back onto the Kafka broker to allow them to be accessed by other services and stored in the InfluxDB database. The server received data sent over LoRaWAN through the TTN MQTT broker.

⑥ It is also published to the Kafka message broker and processed similarly, ending up in the same InfluxDB instance. A series of Grafana dashboards present the data, reading directly from the InfluxDB database.

The mechanical interface was designed to be robust enough to survive potentially thousands of hours strapped to the front of a bicycle (Figure 7) but quick enough to install so that it did not hinder the deployment. The modular architecture of the system simplified its design and management. Each system component interacted through a minimal number of interfaces (for example, the processing scripts interacted exclusively via the Kafka message broker and use a fixed JSON structure). The GPS on board recorded a complete route trace from start to finish. Security for the system was provided using industry standards such as SSH. Simultaneously, the cost was kept low by relying purely on open-source software and free communication technologies.

3.3.2 | Extracted data and its uses and value at different scales

The e-bike study generated a rich dataset, providing information on many aspects of e-bike usage, demonstrating how one type of monitoring device (deployed on multiple bikes) can provide data that is useful to each of the different levels

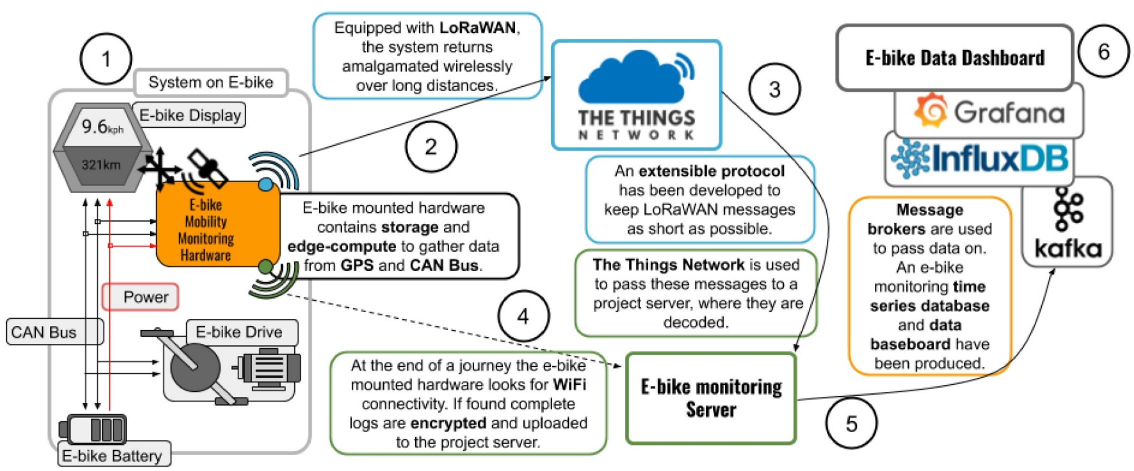

FIGURE 6 E-bike mobility monitoring system diagram.

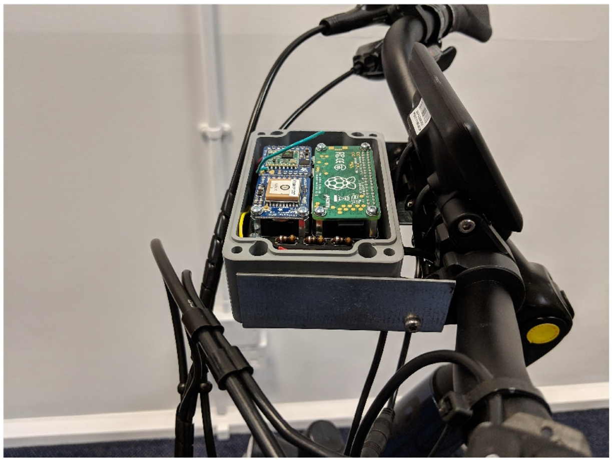

FIGURE 7 E-bike mobility monitoring system with the waterproof cover removed.

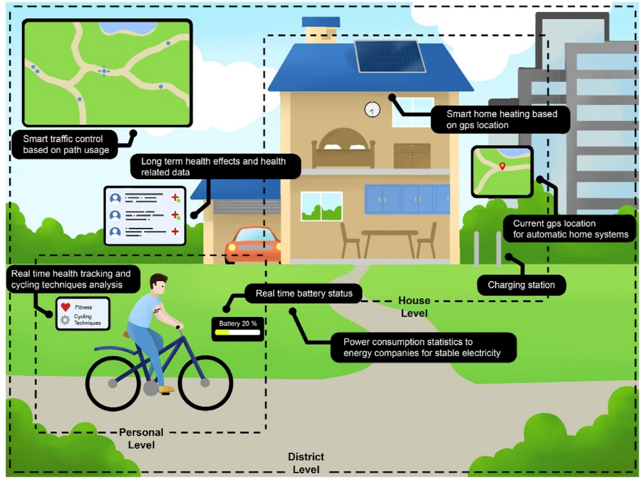

FIGURE 8 How data generated at the personal level can be interlinked with information needs at different scales.

discussed here (i.e. personal, built environment, district and urban). These devices provided the e-bike riders with a detailed account of the exercise they had performed. The data helped end users understand their fitness levels and provided insights that could improve their cycling technique [99].

But generated data can be consumed in different ways at different scales (see e.g. Figure 8). Therefore, it must be processed and visualised differently depending on the target audience. In addition, several different datasets can be amalgamated to increase the insight the monitoring system can deliver. In the example of tracking the electronic bicycle shown in Figure 9, GPS data and pedal torque were overlayed to provide the user with detailed information about the effort they put into their cycling at each moment of the ride.

With almost 3000 journeys recorded by the e-bike monitoring system, the data also built a picture of the popularity of different routes within the city of Bristol's road network (Figure 10), showing which sections cyclists regularly avoid [99]. Such aggregated data can provide valuable insight to planners, such as the e-bike usage heatmap (Figure 10). However, knowing a user's complete journey history could provide personal details such as home and work addresses, potential family and friends' addresses etc. The researchers' sensitivity to ethical and privacy issues led to consideration by design about how data can be anonymised by obscuring the beginning and end of a journey, or breaking the journey down into 'links' and only presenting those widely used links. Each method has advantages and disadvantages, and a compromise must be reached to ensure that the value of the data is maintained without sacrificing data security when shared. Each potential application will have its requirements and so will potentially require fresh consideration and its own post-processing to be done. Data from the e-bike case study has already been shared with the local authority to help them understand which parts of the city would benefit the most from improved cycling infrastructure.

Awareness of these different perspectives (cyclist, planner) ensures that the innovator is able to understand the implications of data scales, the potential value of its analysis, and to tailor the monitoring system and its outcomes to their different needs. Such visibility of perspectives and stakeholder roles was possible under the collaborative ethos that is pervasive throughout this capability. In addition, the study provided a physical, situated-in-the-world testbed where observations could be made about real journeys, and blue skies exploration could safely take place. The Collaboratory brought together people with different skillsets and backgrounds. For the e-bike intervention, it connected researchers with the skills to deploy the appropriate sensors and e-bike modifications. The data collected provided information on how e-bikes could improve community nurses' activities to support old care homes. The project was in partnership with the local hospital and council, providing safe means of mobility during challenging times of a global pandemic. It generated meaningful data on the use of bikes by continuously measuring and providing quantitative metrics combined with qualitative data from interviews and questionnaires to determine the impact of e-bikes on community nurses' activities.

The e-bike study has already formed the basis for other funding applications for further studies, focussing on topics ranging from e-cargo-bike logistics to how e-bike usage can help prevent early mortality in over 55 s.

3.4 | An emerging role for urban observatories?

The Urban Observatories aim to work with citizens, city councils, and organisations to solve urban challenges. Data collection often requires IoT infrastructure to collect, analyse and visualise data. Infrastructure must be designed, implemented, and deployed in the built environment or public spaces. An entity such as a non-profit organisation, university, industry partner, private institution, government, or a collaboration between multiple organisations must take ownership of the design, implementation, and deployment. Observatories as discussed here are capabilities that help manage the complexity of sensing

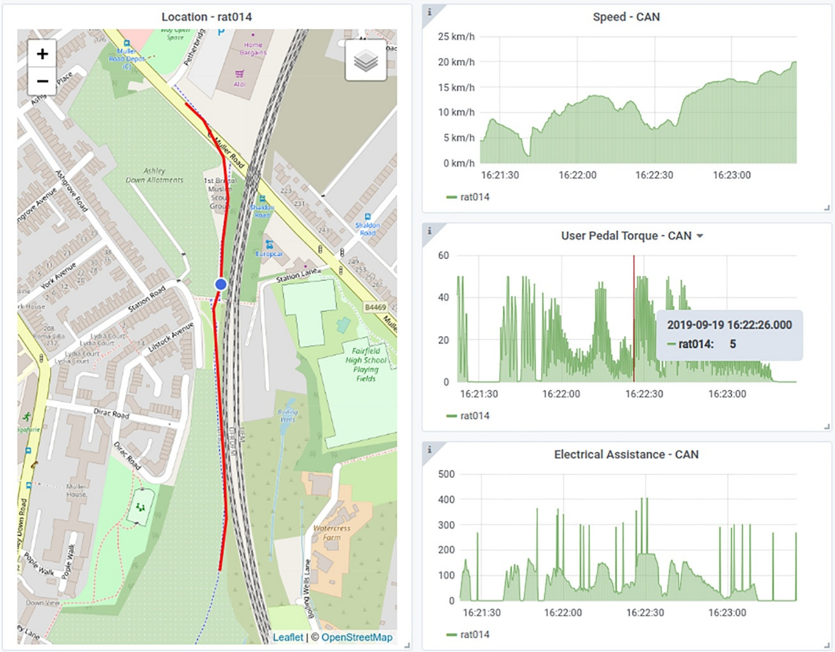

FIGURE 9 Personal-level data showing a user's cycling activity.

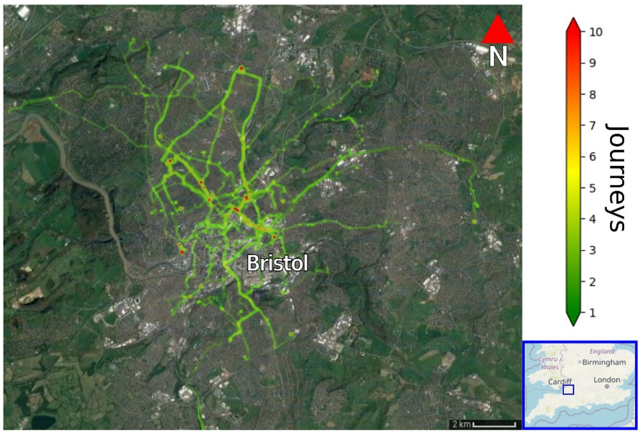

FIGURE 10 City level data showing how often different parts of the city are visited by the monitored e-bikes (June 2019).

initiatives. They support the design process, develop architectures, platforms, and visualisations for the end user and deliver a solution by assembling technology skills. Observatory testbeds provide the ability to test at scale in the real world, outside of lab or simulation, and understand the implications of deployment and other hidden overheads such as value versus cost. For example, the e-bike monitoring device was prototyped in the lab and later deployed in Bristol. The Collaboratory provided hardware sensors and infrastructure for data storage, analysis and visualisation, supporting activities that generate data useful at different levels (from personal to urban).

An Observatory capability has the potential to overcome stereotypical perceptions of academia being remote and only observant of a situation [100] or not willing to 'get their hands dirty'. Observatories can enable the collection, storage, and analysis of city-related data and provide a focal point for researchers, city officials, and other city stakeholders to understand where additional sensing would benefit and appropriately target activities. Cities can institutionalise infrastructures such as urban observatories to facilitate data collection, storage, and sharing with citizens, researchers, and innovators to solve city challenges.

4 | CONCLUSION

In this paper, we contextualise urban sensing and the use of resulting data for city management, as well as explore its potential for tackling urban challenges, value creation and its own challenges. We identified and categorised the types of urban data that can be collected using readily available and accessible IoT devices and examined how this information could be used in asset management and city decision-making, with consideration for its caveats, including privacy, participation and value sharing. Scaling from personal data collection (Table 1) through to city data collection (Table 4), we have identified key generated datasets, highlighted their potential use (e.g. for improving existing or developing new services) and associated value. This output systematises data collection in a transparent hierarchy that can be useful for understanding interdependencies of the related processes, as well as where economies of scale could be built, depending on the priorities of different cities and regions.

We also discussed the emerging concept of Urban Observatories as developed by UN-Habitat and interpreted/realised in the context of UKCRIC, with Bristol's UO as a particular example. We examined their potential role in curating the various IoT data streams effectively and in a trustworthy manner and used a mobility case study to demonstrate how such entities could leverage data collection hierarchies to contribute to the overall objective of supplying quality data for city management.

Overall, we examined the role of citizen-centred interventions and their outcomes, such as datasets created by urban sensing projects in the energy and mobility sectors, and how such individually contributed data have the capacity to generate value at scale. However, valuable data collection does not come without challenges. As mentioned already, citizens' concerns about the security and privacy of their data, transparency of decision-making, and fair sharing of value creation are at the heart of these. We thus argue that, only by institutionalising the collaboration between policy-making, skills and knowledge bodies, with the citizen as the pillar of the triad *innovation*, *enterprise*, and *investment*, communities can be better set for tackling their urban challenges.

AUTHOR CONTRIBUTIONS

Vijay Kumar: Visualisation; writing – original draft. **Sam Gunner**: Data curation; formal analysis; investigation; resources; writing – original draft. **Maria Pregnolato**: Formal analysis; writing – review & editing. **Patrick Tully**: Project administration; validation; writing – review & editing. **Nektarios Georgalas**: Supervision; validation. **George Oikonomou**: Supervision; writing – review & editing. **Stylianos Karatzas**: Project administration; resources. **Theo Tryfonas**: Conceptualisation; funding acquisition; methodology; supervision; writing – review & editing.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

Data sharing not applicable to this article as no datasets were generated or analysed during the current study.

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REFERENCES

1. British Standards Institute(BSI). PD 8100:2015—Smart Cities Overview – Guide (2015)
2. UN DESA: The sustainable development goals report 2022—July 2022. [Online]. https://unstats.un.org/sdgs/report/2022/ (2022)
3. Shrouf, F., Ordieres, J., Miragliotta, G.: Smart factories in industry 4.0: a review of the concept and of energy management approached in production based on the internet of things paradigm. In: 2014 IEEE International Conference on Industrial Engineering and Engineering Management, pp. 697–701. IEEE (2014)
4. Miori, V., Russo, D.: Improving life quality for the elderly through the social internet of things (siot). In: 2017 Global Internet of Things Summit (GIoTS), pp. 1–6. IEEE (2017)
5. Belfast CIty Council. The Belfast Agenda (2014). [Online]. https://smartbelfast.city/wp-content/uploads/2018/04/Belfast-Agenda-3.9MB-PDF.pdf
6. Bristol City Council: One city plan 2020. [Online]. https://www.bristolonecity.com/wp-content/uploads/2020/01/One-City-Plan_2020.pdf. 1–64 (2020)
7. Catlett, C.E., et al.: Array of things: a scientific research instrument in the public way. In: Proceedings of the 2nd International Workshop on Science of Smart City Operations and Platforms Engineering—SCOPE '17, pp. 26–33 (2017). [Online]. http://dl.acm.org/citation.cfm?doid=3063386.3063771
8. Strain, T., Gunner, S., Wilson, E.: Estimation of vehicle counts from the structural response of a bridge. In: 2019 International Conference on Smart Infrastructure and Construction (ICSIC 2019). Thomas Telford (ICE Publishing), United Kingdom (2019)
9. Ho, S., et al.: Using smartphone accelerometry to assess the relationship between cognitive load and gait dynamics during outdoor walking. Sci. Rep. 9(1), 3119 (2019). https://doi.org/10.1038/s41598-019-39718-w
10. Tryfonas, T., et al.: Causal loop mapping of emerging energy systems in project twinergy: towards consumer engagement with group model building. In: Proceedings of the 15th International Conference on PErvasive Technologies Related to Assistive Environments, pp. 254–259 (2022)
11. Chen, Y., Han, D.: Water quality monitoring in smart city: a pilot project. Autom. ConStruct. 89, 307–316 (2018). [Online]. Available. https://doi.org/10.1016/j.autcon.2018.02.008
12. Nepomuceno, D., Tryfonas, T., Vardanega, P.: Residential damp detection with temperature and humidity urban sensing. In: DeJong, M., Schooling, J., Viggiani, G. (eds.) International Conference on Smart Infrastructure and Construction 2019 (ICSIC), pp. 605–611. Thomas Telford (ICE Publishing), United Kingdom (2019)
13. Fulk, G.D., et al.: Accuracy of 2 activity monitors in detecting steps in people with stroke and traumatic brain injury. Phys. Ther. 94(2), 222–229 (2014). [Online]. Available. https://doi.org/10.2522/ptj.20120525
14. Fafoutis, X., et al.: Designing wearable sensing platforms for healthcare in a residential environment. EAI Endorsed Trans. Pervasive Health Technol. 17(12) (2017)
15. Kortelainen, J.M., van Gils, M., Pärkkä, J.: Multichannel bed pressure sensor for sleep monitoring. In: 2012 Computing in Cardiology, pp. 313–316. IEEE (2012)
16. Huang, M., Gibson, I., Yang, R.: Smart chair for monitoring of sitting behavior. KnE Eng. 2(2), 274 (2017). [Online]. Available. https://doi.org/10.18502/keg.v2i2.626
17. Vafeas, A., et al.: Energy-efficient, noninvasive water flow sensor. In: Proc. SMARTCOMP, pp. 139–146. IEEE (2018)
18. Ghandeharioun, A., et al.: "kind and grateful": a context-sensitive smartphone app utilizing inspirational content to promote gratitude. Psychol. Well-Being 6(1), 1–21 (2016). https://doi.org/10.1186/s13612-016-0046-2
19. Brasche, S., Bischof, W.: Daily time spent indoors in German homes – baseline data for the assessment of indoor exposure of German occupants. Int. J. Hyg Environ. Health 208(4), 247–253 (2005). [Online]. Available. https://doi.org/10.1016/j.ijheh.2005.03.003
20. Von Neida, B., Manicria, D., Tweed, A.: An analysis of the energy and cost savings potential of occupancy sensors for commercial lighting systems. J. Illum. Eng. Soc. 30(2), 111–125 (2001). https://doi.org/10.1080/00994480.2001.10748357
21. Ratti, C.F.: Localized thermal management system. uS Pat. App 14/856, 679 (2016)
22. Valancius, R., et al.: Solar photovoltaic systems in the built environment: today trends and future challenges. J. Sustain. Architect. Civ. Eng. 23(2), 25–38 (2018). https://doi.org/10.5755/j01.sace.23.2.21268
23. Chowdhury, N., et al.: EV charging: separation of green and Brown energy using IoT. In: Proceedings of the 2016 ACM International Joint Conference on Pervasive and Ubiquitous Computing: Adjunct, pp. 674–677 (2016)
24. Bourgeois, J., et al.: Using participatory data analysis to understand social constraints and opportunities of electricity demand-shifting. In:

Proceedings of the 2014 Conference ICT for Sustainability (2014). [Online]. http://www.atlantis-press.com/php/paper-details.php?id=13467
25. Cherrington, R., et al.: The feed-in tariff in the UK: a case study focus on domestic photovoltaic systems. Renew. Energy 50, 421–426 (2013). https://doi.org/10.1016/j.renene.2012.06.055
26. Ofwat: Out in the cold - water companies' response to the 'beast from the east. [Online]. www.ofwat.gov.uk.39 (2018)
27. Ranjan, V., et al.: The internet of things (iot) based smart rain water harvesting system. In: 2020 6th International Conference on Signal Processing and Communication (ICSC), pp. 302–305. IEEE (2020)
28. Rezaei, H., Melville-Shreeve, P., Butler, D.: Smart Rainwater Management Systems Powered by the Internet of Things: A uk Case Study
29. Melville-Shreeve, P.: Building Resilient Networks for Severe Weather (2018). [Online]. http://www.overtheairanalytics.com/802-2/. accessed 17-December-2018
30. Mohottige, I.P., et al.: Role of campus wifi infrastructure for occupancy monitoring in a large university. In: 2018 IEEE International Conference on Information and Automation for Sustainability (ICIAfS), pp. 1–5. IEEE (2018)
31. Banerjee, T., et al.: Sit-to-stand measurement for in-home monitoring using voxel analysis. IEEE J Biomed. Health Inf. 18(4), 1502–1509 (2014). https://doi.org/10.1109/jbhi.2013.2284404
32. Stone, E.E., Skubic, M.: Fall detection in homes of older adults using the microsoft kinect. IEEE J. Biomed. Health Inf. 19(1), 290–301 (2015). https://doi.org/10.1109/jbhi.2014.2312180
33. Meadows-Klue, D.: Inside the smart home. J. Direct, Data Digital Mark. Pract. 5(3), 307–308 (2004). https://doi.org/10.1057/palgrave.im.4340249
34. Wouters, L., et al.: Fast, furious and insecure: passive keyless entry and start systems in modern supercars. IACR Trans. Cryptographic Hardw. Embed. Syst. 2019(3), 66–85 (2019). https://doi.org/10.46586/tches.v2019.i3.66-85
35. Roubein, R.: Apps Help Reduce, Reuse, Recycle, 02B–02B. USA Today (2011)
36. Organization, W.H., et al.: WHO Guidelines for Indoor Air Quality: Selected Pollutants. World Health Organization, Regional Office for Europe (2010)
37. Camprodon, G., et al.: Smart citizen kit and station: an open environmental monitoring system for citizen participation and scientific experimentation. HardwareX 6, e00070 (2019). https://doi.org/10.1016/j.ohx.2019.e00070
38. Hamm, A.: Particles matter: a case study on how civic iot can contribute to sustainable communities. In: Proceedings of the 7th International Conference on ICT for Sustainability, pp. 305–313 (2020)
39. ATMO: Atmo - air quality monitors for consumers and businesses. [Online]. https://atmotube.com/ (2022)
40. Zhu, N., et al.: Bridging e-health and the internet of things: the sphere project. IEEE Intell. Syst. 30(4), 39–46 (2015). https://doi.org/10.1109/mis.2015.57
41. Pereira, J.: Measuring transportation traffic, mobility and accessibility. ITEA J. 73(10), 28–32 (2010). [Online]. www.joaopereira.com
42. MK food revolution launching local food passports funded by MK: smart, (2022). [Online]. https://communityactionmk.org/2015/11/20/mk-food-revolution-launching-l%20ocal-food-passports-funded-by-mksmart/
43. West, L.R.: Strava: challenge yourself to greater heights in physical activity/cycling and running. Br. J. Sports Med. 49(15), 1024–1024 (2015). https://doi.org/10.1136/bjsports-2015-094899
44. Dirige in2 Social: Walkers group santander: reducing loneliness through outdoor activities that strengthen social and mental resilience of citizens. [Online]. https://organicity.eu/experiment/walkers-group-santander-reducing-loneliness-outdoor-activities-strengthen-social-mental-resilience-citizens/ (2017). accessed 17-December-2018
45. Walks in the City: improving the wellbeing of senior citizens and their neighbourhoods, (2022). [Online]. http://organicity.eu/experiment/walks-in-the-city-2/
46. Weeks, I., Holden, B., Stanoev, A.: A low power system for synchronising buffered air quality data. In: 2022 IEEE International Symposium on Measurements & Networking (M&N), pp. 1–6. IEEE (2022)
47. Daepp, M.I.G., et al.: Eclipse: an end-to-end platform for low-cost, hyperlocal environmental sensing in cities. In: 2022 21st ACM/IEEE International Conference on Information Processing in Sensor Networks (IPSN), pp. 28–40 (2022)
48. Lanza, J., et al.: Large-scale mobile sensing enabled internet-of-things testbed for smart city services. Int. J. Distributed Sens. Netw. 11(8), 785061 (2015). [Online]. Available. https://doi.org/10.1155/2015/785061
49. Traffic Pollution Flow: Traffic Controlled by Air Quality (2018). [Online]. https://organicity.eu/experiment/traffic-controlled-air-quality/. accessed 17-December-2018
50. Sensifai: Brussels Qualitative and Quantitative Noise Map (2017). [Online]. http://organicity.eu/experiment/brussels-qualitative-quantitative-noise-map/. accessed 17-December-2018
51. Corwin, S., Johnson, T.L.: The role of local governments in the development of China's solar photovoltaic industry. Energy Pol. 130, 283–293 (2019). https://doi.org/10.1016/j.enpol.2019.04.009
52. Kelly, M.: Lighting the way: Norway's auto-dimming street lamps get brighter only as traffic approaches and then return to 20 percent power - and will help reduce country's carbon footprint. [Online]. https://www.dailymail.co.uk/news/article-5226533/Norways-auto-dimming-street-lights-brighten-cars.html (2018). accessed 17-December-2018
53. Medvedev, A., et al.: Waste management as an iot-enabled service in smart cities. In: Internet of Things, Smart Spaces, and Next Generation Networks and Systems, pp. 104–115. Springer (2015)
54. USC-UPCT-CUD-UVIGO: Conversational interfaces for urban data. [Online]. http://organicity.eu/experiment/conversational-interfaces-urban-data/ (2018). accessed 17-December-2018
55. Bristol.Gov.UK: State of the Art Operations Centre Opens in Bristol (2018). [Online]. https://news.bristol.gov.uk/news/state-of-the-art-operations-centre-opens-in-bristol-2. accessed 17-May-2019
56. TfL: Review of the TfL WiFi Pilot (2017). [Online]. http://content.tfl.gov.uk/review-tfl-wifi-pilot.pdf
57. Calabrese, F., et al.: Real-time urban monitoring using cell phones: a case study in rome. IEEE Trans. Intell. Transport. Syst. 12(1), 141–151 (2010). https://doi.org/10.1109/tits.2010.2074196
58. Adler, L.: How Smart City Barcelona Brought the Internet of Things to Life (2018). [Online]. https://datasmart.ash.harvard.edu/news/article/how-smart-city-barcelona-brought-the-internet-of-things-to-life-789. accessed 17-December-2018
59. Giang, N.K., et al.: Cityflow: exploiting edge computing for large scale smart city applications. In: 2019 IEEE International Conference on Big Data and Smart Computing (BigComp), pp. 1–4. IEEE (2019)
60. Bristol.Gov.UK: How a Bike Sharing Scheme Benefits Everyone in Manchester (2018). [Online]. https://cityverve.org.uk/how-a-bike-sharing-scheme-benefits-everyone-in-manchester/. accessed 17-May-2019
61. Idee, P.: Madame Mayor, I Have an Idea - Your Ideas for Paris — the Digital Platform for the Paris of Tomorrow (2020). [Online]. https://idee.paris.fr/
62. Bojic, I., Marra, G., Naydenova, V.: Online Tools for Public Engagement: Case Studies from Reykjavik (2016). arXiv preprint arXiv:1611.08981
63. Hecht, B.: Carticipe/ Debatomap (2018). [Online]. https://carticipe.net/carticipe-debatomap-in-english/. accessed 17-December-2018
64. Four, T.: Ushahidi. [Online]. https://www.ushahidi.com/ (2018). accessed 17-December-2018
65. OpenStreetMap: Openstreetmap, (2018). accessed 17-December-2018. [Online]. https://www.openstreetmap.org
66. OpenPlans: Shareabouts, (2018). accessed 17-December-2018. [Online]. https://github.com/openplans/shareabouts
67. Cyclestreets UK-wide cycle journey planner and photomap, (2022). accessed 4-December-2021. [Online]. https://www.cyclestreets.net/
68. Robinson, C., Franklin, R.S.: The sensor desert quandary: what does it mean (not) to count in the smart city? Trans. Inst. Br. Geogr. 46(2), 238–254 (2021). [Online]. Available. https://doi.org/10.1111/tran.12415

69. Bristol City Council: One city plan climate strategy. [Online]. https://www.bristolonecity.com/wp-content/uploads/2020/02/one-city-climate-strategy.pdf (2020).164
70. Lockwood, F.: Bristol's smart city agenda: vision, strategy, challenges and implementation. IET Smart Cities 2(4), 208–214 (2020). [Online]. Available. https://doi.org/10.1049/iet-smc.2020.0063
71. Rye Tait Consulting: Surveying UK connected places. [Online]. https://www.gov.uk/government/publications/uk-connected-places-survey (2022).175
72. Armitt, J.: The Armitt Review: An Independent Review of Long Term Infrastructure Planning Commissioned for Labour's Policy Review. Labour Party (2013)
73. UKCRIC: Ukcric missions. [Online]. https://www.ukcric.com/about-ukcric/missions/ (2022). accessed 4-Nov-2022
74. UN-Habitat. Urban Observatories (2021). [Online]. https://data.unhabitat.org/pages/urban-observatories
75. James, P., et al.: Realizing smart city infrastructure at scale, in the wild: a case study. Front. Sustain. Cities 4 (2022). https://doi.org/10.3389/frsc.2022.767942
76. James, P., et al.: Smart cities and a data-driven response to covid-19. Dialogues in Hum. Geogr. 10(2), 255–259 (2020). https://doi.org/10.1177/2043820620934211
77. Cosgrave, E., Arbuthnot, K., Tryfonas, T.: Living labs, innovation districts and information marketplaces: a systems approach for smart cities. Proc. Comput. Sci. 16, 668–677 (2013). 2013 Conference on Systems Engineering Research. [Online]. Available. https://doi.org/10.1016/j.procs.2013.01.070
78. European Network of Living Labs. What Are Living Labs (2014). [Online]. https://www.brookings.edu/articles/rise-of-innovation-districts/
79. Katz, B., Wagner, J.: The rise of innovation districts: a new geography of innovation in America. [Online]. https://enoll.org/about-us/what-are-living-labs/ (2023)
80. Burtan, D., et al.: The nature effect in motion: visual exposure to environmental scenes impacts cognitive load and human gait kinematics. R. Soc. Open Sci. 8(1), 201100 (2021). https://doi.org/10.1098/rsos.201100
81. Bristol Infrastructure Collaboratory. Travel Exhibition (2022). [Online]. https://www.bristol.ac.uk/engineering/research/ukcricbristol/collaboratory/travel-exhibition/. accessed 4-Nov-2022
82. Clifton suspension bridge trust, (2022). [Online]. https://cliftonbridge.org.uk/about-us/
83. Sengupta, U., Sengupta, U.: Why government supported smart city initiatives fail: examining community risk and benefit agreements as a missing link to accountability for equity-seeking groups. Front. Sustain. Cities 4 (2022). [Online]. Available. https://doi.org/10.3389/frsc.2022.960400
84. Sista, E., De Giovanni, P.: Scaling up smart city logistics projects: the case of the smooth project. Smart Cities 4(4), 1337–1365 (2021). [Online]. Available. https://doi.org/10.3390/smartcities4040071
85. Barcena, M.B., Wueest, C.: Insecurity in the internet of things. Secur. Response, Symantec, 20 (2015)
86. Lin, H., Bergmann, N.: Iot privacy and security challenges for smart home environments. Information 7(3), 44 (2016). [Online]. Available. https://doi.org/10.3390/info7030044
87. Fafoutis, X., et al.: Privacy leakage of physical activity levels in wireless embedded wearable systems. IEEE Signal Process. Lett. 24(2), 136–140 (2016). https://doi.org/10.1109/lsp.2016.2642300
88. Fussey, P., Murray, D.: Independent Report on the london metropolitan Police Service's Trial of Live Facial Recognition Technology (2019)
89. Liang, F., et al.: Constructing a data-driven society: China's social credit system as a state surveillance infrastructure. Pol. Internet 10(4), 415–453 (2018). https://doi.org/10.1002/poi3.183
90. Chorzempa, M., Triolo, P., Sacks, S.: China's Social Credit System: A Mark of Progress or a Threat to Privacy? Peterson Institute for International Economics, Policy Briefs PB18-14 (2018). [Online]. https://ideas.repec.org/p/iie/pbrief/pb18-14.html
91. Mishra, K.N., Chakraborty, C.: A novel approach toward enhancing the quality of life in smart cities using clouds and iot-based technologies. In: Digital Twin Technologies and Smart Cities, pp. 19–35. Springer (2020)
92. Sharida, A., Hamdan, A., Al-Hashimi, M.: Smart cities: the next urban evolution in delivering a better quality of life. In: Toward Social Internet of Things (SIoT): Enabling Technologies, Architectures and Applications, pp. 287–298. Springer (2020)
93. Rostami, A., et al.: Being hacked: understanding victims' experiences of {IoT} hacking. In: Eighteenth Symposium on Useable Privacy and Security (SOUPS 2022), pp. 613–631 (2022)
94. Münch, D., et al.: Data anonymization for data protection on publicly recorded data. In: International Conference on Computer Vision Systems, pp. 245–258. Springer (2019)
95. Hauser, O.P., et al.: Invisible inequality leads to punishing the poor and rewarding the rich. Behav. Publ. Pol. 5(3), 333–353 (2021). https://doi.org/10.1017/bpp.2019.4
96. Lee, I., Lee, K.: The internet of things (iot): applications, investments, and challenges for enterprises. Bus. Horiz. 58(4), 431–440 (2015). [Online]. Available. https://doi.org/10.1016/j.bushor.2015.03.008
97. van Capelleveen, G., et al.: The footprint of things: a hybrid approach towards the collection, storage and distribution of life cycle inventory data In: ICT4S, pp. 350–364 (2018)
98. Baccarne, B., Mechant, P., Schuurman, D.: Empowered cities? an analysis of the structure and generated value of the smart city ghent. In: Smart City, pp. 157–182. Springer (2014)
99. Gunner, S., Wilson, R., Tryfonas, T.: Using telematics to gather user behaviour data from a fleet of electric bicycles. [Online]. https://ercim-news.ercim.eu/en127/special/using-telematics-to-gather-user-behaviour-data-from-a-fleet-of-electric-bicycles (2021)
100. Ahlgren, B., Hidell, M., Ngai, E.C.-H.: Internet of things for smart cities: interoperability and open data. IEEE Internet Comput. 20(6), 52–56 (2016). https://doi.org/10.1109/mic.2016.124

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